REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
19-12-2002

2. REPORT DATE
FINAL REPORT

3. DATES COVERED *(From - To)*
5/1/1999 - 4/30/2002

4. TITLE AND SUBTITLE
Prediction of the low frequency wave field on open coastal beaches

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-99-1-0490

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Arch. & Marine Eng
University of Michigan
Ann Arbor, MI 48109

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Regents of the University of Michigan
Division of Research development
3003 South State St.
Ann Arbor, MI 48109-1274

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This work involves the development of a model for the prediction of low frequency motions (LFM) in the nearshore zone. This work concentrates on the identification of processes that generate LFM's as well as those that limit their growth. Several such mechanisms are identified and studied, and their importance in the prediction of LFM's are assessed.

15. SUBJECT TERMS
Nearshore circulation, numerical modeling, Prediction of circulation.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPONE NUMBER (*Include area code*)

Prediction of the Low Frequency Wave Field on Open Coastal Beaches

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Award Numbers: N00014-99-1-0490

LONG-TERM GOALS

The long-term goal of this study is to arrive at a predictive understanding of the time varying circulation in the nearshore region given only information about the incident wave field and bottom bathymetry. Predictions should include information about the kinematics of low frequency motions (their wavenumbers and frequencies) as well as information about their dynamics (energetics).

OBJECTIVES

The scientific objectives of the study are related to gaining an understanding of the important features of the nearshore circulation field, so that quantitative predictions about the circulation field at a given site can be reliably made. Specific objectives include: 1. The assessment of the impact of specific features of wave groups on edge wave development and the prediction of the finite amplitude edge wave field resulting from a balance between the wave group forcing and dissipation mechanisms. 2. The assessment of the degree to which non-uniformities in the bottom bathymetry (both abrupt and gradual) affect the resulting low frequency wave climate. 3. The assessment of the importance of interactions between different modes of time-varying motions in the nearshore region, as well as interactions between these modes and the incident wave field. 4. To arrive at a predictive understanding of low frequency motions.

APPROACH

The approach is to use a numerical model to assess our understanding of time-varying circulation in the nearshore region. The finite amplitude behavior of low frequency motions in the nearshore region is a function of a balance between processes that generate these motions and processes that dissipate them. The approach used here is to isolate several generation, dissipation processes as well as processes affecting the evolution of the motions in a modeling effort and start with the simplest possible theory to model the processes. More complicated and full treatments are introduced in a step-by-step fashion resulting in an understanding of the effects of the processes and their parameterizations on the resulting circulation field.

We are utilizing a model that solves the time-dependent shallow water equations with additional terms to account for the effects of forcing and damping (Özkan-Haller and Kirby, 1997). Although only valid in shallow water, these equations can model the leading order behavior of both low frequency gravity

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motions (edge waves) and vorticity motions (shear waves). Eight partial differential equations are solved simultaneously to obtain the evolution of eight unknowns; namely, the phase-averaged water surface elevation, the phase-averaged cross-shore and longshore velocities, the horizontal shoreline runup due to low frequency motions, the incident wave energy, the incident wave wavenumber, the local incident wave direction, and the water depth. The effects of bottom friction, turbulent momentum mixing, incident wave transformation and forcing, wave-current interaction and arbitrary bottom movement, are included in a rudimentary fashion. We begin our modeling effort by generating edge waves and shear waves in idealized conditions, and progressively move to more realistic situations where these motions are allowed to coexist and interact.

WORK COMPLETED

We have completed the implementation of an equation governing the behavior of the time-varying incident wave energy in order to simulate the evolution of incoming wave groups. We subsequently analyzed the generation of edge waves by a bi-chromatic wave field, including the effects of nonlinear wave interactions as well as the effect of a moving breakpoint (Lippmann *et al.*, 1997). We successfully generated various edge wave modes of finite amplitude and have isolated the effects of nonlinear generation mechanisms and generation due to a moving breakpoint. Also under investigation was the half-life of the generated waves. A finding suggested that finite amplitude edge waves can exist in both a high forcing-high dissipation environment as well as a low forcing-low dissipation environment. We have analyzed measurements obtained previously on a pocket beach to gain information about the dissipational climate in which edge waves may exist.

We have completed the implementation of the time dependent equations that approximate the behavior of phase-averaged properties of the incident waves; namely, the incident wave energy, the wavenumber and the local angle of incidence. The energy equation for the incident waves is used to model the former while the conservation of wavenumber principle is introduced to model the latter two variables. These model equations include effects of the current velocities. In this manner the forcing of wave-induced currents is modeled while taking the effects of the generated currents on the wave field into account. We have analyzed wave-current interaction effects in environments with varying amounts of dissipation due to bottom friction. We concentrated on the flow properties of the resulting currents as well as propagation speeds of the resulting motions. Also of interest was the effect on the shoreline runup.

We have completed work on an analytical model to isolate unstable behavior in the surf zone due to the interaction of unsteady currents and the incident wave field. Utilizing this linear instability model we identified unstable behavior in a system that includes unsteady currents as well as an unsteady wave field due to the effects of the currents on the incident waves.

RESULTS

We have analyzed several aspects of resonant edge wave forcing. We have found that the final amplitude of the resulting edge wave is a function of the strength of the forcing and the strength of the dissipation. In fact, a balance between the two processes exist, such that an almost identical edge wave field can be obtained in a situation where both the forcing and dissipation are weak as well as in a situation where both the forcing and dissipation are strong. Although such two edge waves might have a similar finite amplitude, the distinction between the dissipational environments is significant. In

particular, if the forcing ceases in a weak dissipational environment, the edge waves can persist for long periods of time, can travel large distances, and can be detected in areas relatively far away from their generation site. In this case, the edge waves that are observed during field experiments may show little relation to the specific incident wave field that exists simultaneously at the measurement site, since the edge waves were remotely generated by a potentially different wave field. Hence, it is important to know the dissipational character of a beach on which edge waves exist.

Since direct measurements of the dissipational character of a beach are not available, we turned to measurements of the edge wave field on a pocket beach carried out during a previous study to answer questions related to the dissipational character of that beach. The beach in question was a pocket beach on the north coast of Spain and data from a longshore array of 5 current meters was readily available. The idea was to pinpoint whether standing or progressive waves were being observed on this narrow pocket beach in order to obtain information about the character of the dissipation there. Evidence of standing edge waves has, to date, been sparse, suggesting that the dissipation on natural beaches was strong enough so that edge waves reflected off the side walls of a pocket beach were dissipated quickly as they propagated away from the reflector. (Note that the reflected waves will not be actively forced and hence correspond to free waves that are subject to amplitude decay due to friction.) In contrast, on a pocket beach in a low frictional environment, a standing resonant pattern is expected where the longshore length scales of the edge waves are a function of the longshore width of the beach. Such resonances should be readily observed in a low dissipational environment in the form of resonant peaks in the frequency spectrum of the edge waves. These peaks are expected to be broadened for a higher dissipational environment. In a highly dissipative environment, the broadening of the peaks should be so pronounced that the peaks are virtually indistinguishable from each other. Our findings (Özkan-Haller *et al.*, 2001) suggest that the edge waves on the studied beach exist in a relatively low frictional environment where resonances can be observed (see Figure 1), although the resonant peaks are somewhat broad indicating a detuned resonance (in other words, friction is still an important process).

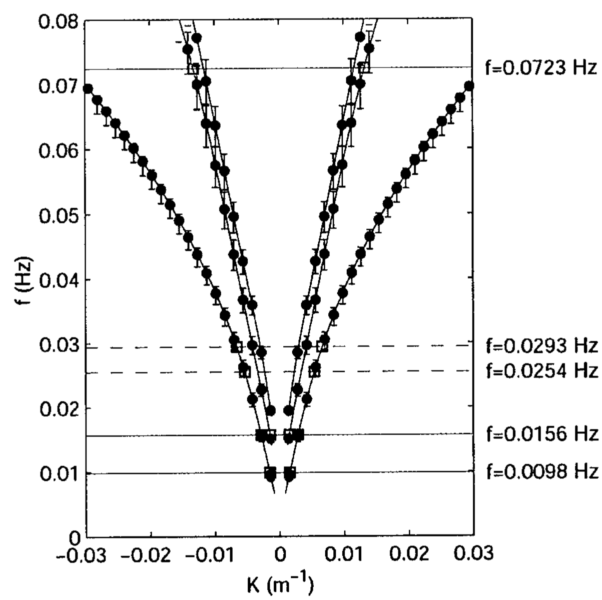

Figure 1: Theoretical edge wave resonances (bullets) and observed edge waves (red squares) on a pocket beach.

One mechanism identified by Lippmann *et al.* (1997) for edge wave generation is related to the temporally and spatially varying surf zone width. The temporally and spatially variable breakpoint

poses significant resolution requirements on a numerical model since the motion can at times occur over small spatial scales (compared to the surf zone width), yet has to be fully resolved in space and time. We sought to find out the importance of this generation mechanism in the prediction of the final edge wave amplitude. We found (see Figure 2) that about 70% of the final amplitude can be predicted if the moving breakpoint is neglected.

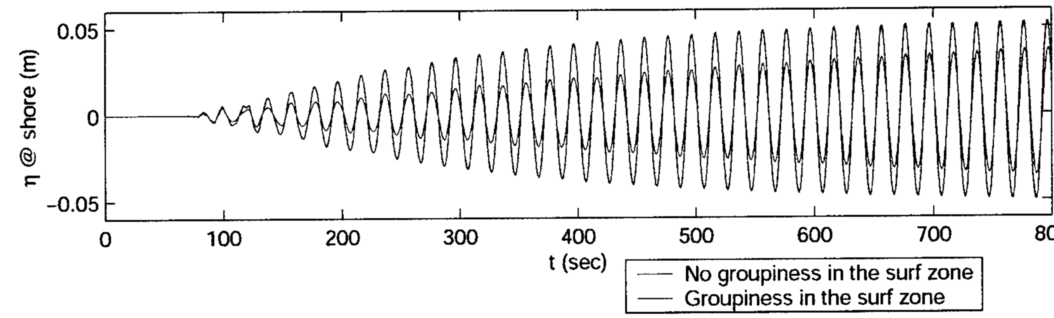

Figure 2: Time series of surface elevation near the shoreline assuming a moving (blue line) and stationary (red line) breakpoint.

In nature, wave groups are broad banded and can occur at a variety of frequencies and longshore wavenumbers. We began our simulations of a broad banded forcing function by utilizing artificial forcing functions. One motivation here was to investigate whether or not the final edge wave field was a strong function of the details of the forcing. As a first step we considered the situation at Leadbetter Beach, CA on February 4, 1980. Data for this day was analyzed by Oltman-Shay and Guza (1987) and they found the presence of a broad banded edge wave field.

We assumed that the incident wave field can be characterized by a narrow banded spectrum, so that it can be approximated by a single wave component with modulated amplitude. However, the amplitude spectrum is assumed to be broad. Our first case involves a "white" amplitude spectrum (Case 1), the second case considers a more realistic amplitude spectrum that decays with frequency (Case 2). We utilize a domain size of 1km x 1 km and use an incident carrier wave with frequency f=0.07 Hz, direction $\theta=32°$ and primary wave height $H_1=0.44$ m. The friction coefficient is set at $c_f=0.003$.

We find that a significant portion of the energy (> 60 %) falls on or near edge wave dispersion curves (see Figure 3). The remaining energy is distributed among forced infragravity waves. This percentage is consistent with observations of Oltman-Shay and Guza (1987). We also find that the excitation of a particular edge wave is not a strong function of details of forcing. However, the energy content and distribution is a strong function of details of forcing.

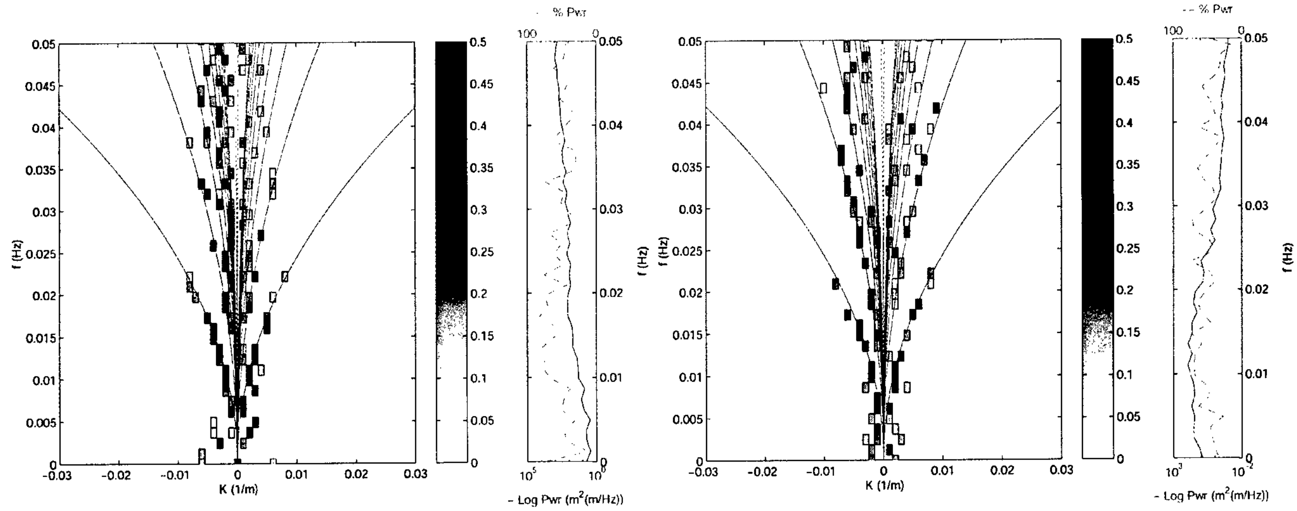

Figure 3: Frequency-longshore wavenumber spectrum of shoreline runup for Case 1 (left panel) and Case 2 (right panel). The boxes represent the percentage of energy that resides within the wavenumber and frequency bin. Only bins with more than 10% energy are shown. The width and height of the boxes are the wavenumber and frequency bandwidth, respectively. The edge wave dispersion lines for a slope of 0.038 (red line) and the leaky wave cut-off (green) are also shown. The right panel shows the power density as well as the percent of the total energy at a given frequency that is accounted for by the boxes in the left panel.

During our investigation of the effect of wave-current interaction on finite amplitude shear instabilities of the longshore current, we found that the offshore extent of the resulting motions is limited significantly by the presence of wave-current interaction, so that the signature of the instabilities offshore of the surf zone is limited (Figure 4). On the other hand, we found that this signature is significantly more pronounced within the shoreline runup when wave-current interaction is considered (Figure 5(a)). Analyzing the wave-current interaction terms within the energy equation for the wave motion (Figure 5(c)) we found that in areas where the currents oppose the waves (see Figure 5(b)) , the wave field gains energy due to work done by the circulation on the waves. In areas where the circulation is co-linear with the wave propagation direction, the opposite occurs. This effects introduces an asymmetry causing the offshore extent of the resulting circulation to be limited. Also, any offshore directed jets that are generated due to the finite amplitude shear instabilities cause the wave field to refract around them. The effect of the refraction causes variations in the wave angle of incidence near the shore (Figure 5(e)) setting up a variation in the longshore current forcing near the shoreline (Figure 5(d)). Our simulations thus suggest that the enhanced fluctuations near the shoreline are the result of a forced circulation pattern that is set up shoreward of any localized cross-shore features in the circulation in mid-surf zone (see Özkan-Haller and Li, 2002).

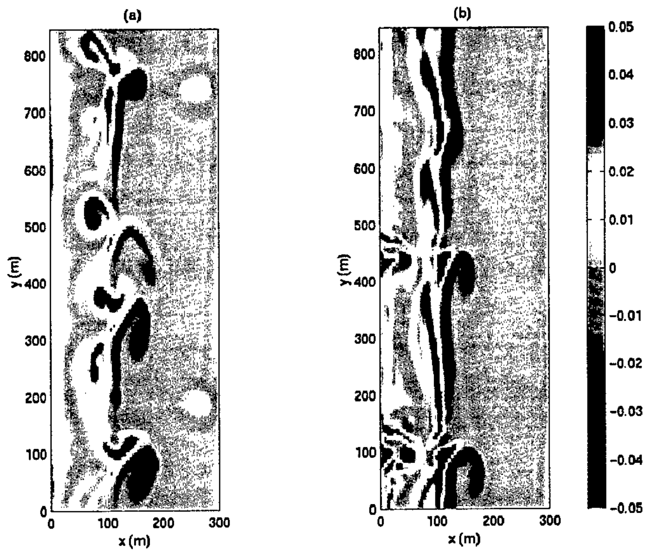

Figure 4: Snapshots of vorticity for shear instabilities on a barred beach with low frictional dissipation (c_f=0.004) (a) neglecting and (b) including wave-current interaction.

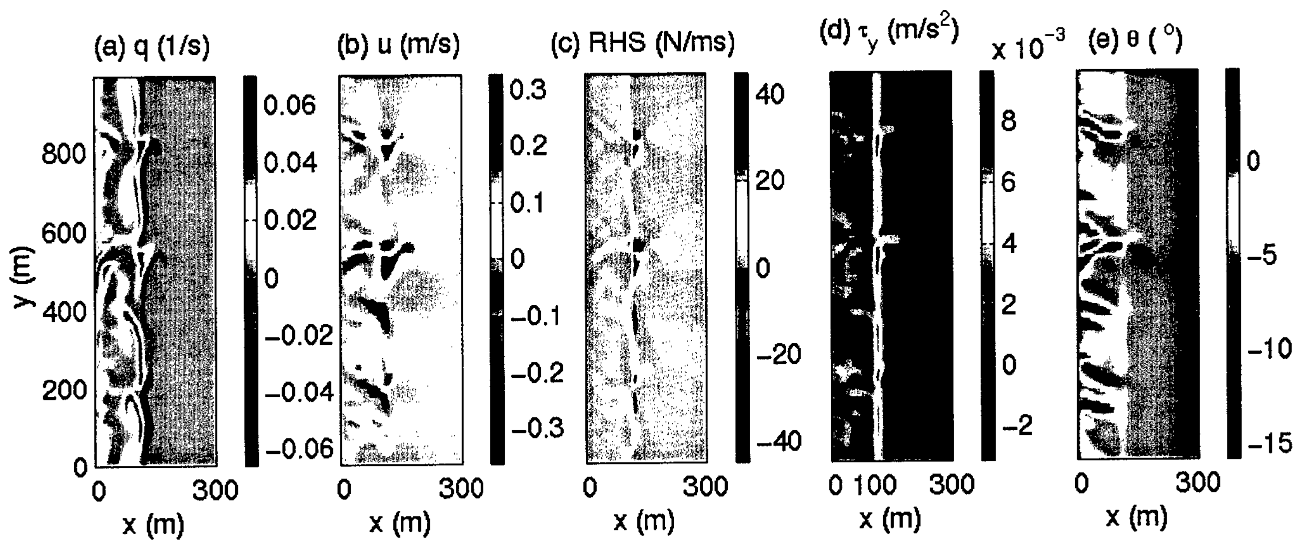

Figure 5: Snapshots for a circulation field involving the instability of a longshore current that flows in the +y-direction. Depicted are (a) the vorticity, (b) the cross-shore velocity, (c) the wave-current interaction terms within the energy equation for the wave motion (see Özkan-Haller and Li, 2002), (d) longshore component of the wave forcing, and (e) local angle of wave incidence, where x points offshore and y points alongshore. Of note are areas where the current field performs work on the wave field, causing it to gain energy (red areas in panel (c)). Note that these coincide with offshore directed flow features (panel (b)). These also cause refraction of the incident wave field (panel (e)), which, in turn, cause variations in the wave forcing of the circulation (panel (d)), ultimately leading to strong fluctuations in the velocities near the shoreline, which are absent when wave-current interaction is neglected.

Our simulations on the nonlinear evolution of shear instabilities of the longshore current also suggest that the onset of the instability is delayed when wave-current interaction is taken into account (see Özkan-Haller and Li, 2002). This finding suggests that the initial linear growth rate of the instability is

reduced by the presence of wave-current interaction. A way to isolate the mechanism by which this occurs is to carry out a linear instability analysis of the system of seven equations that form the basis for the nonlinear model that was utilized. We start by analyzing the linear instability of a simplified system of equations assuming wave-current interaction can be neglected and the low frequency motions are neither actively forced nor dissipated. In this case, the linear instability analysis gives information about both the gravity and the vorticity modes that exist as solutions to this system. The instability analysis assumes that the frequency of the solutions can be a complex number, where a positive complex part indicates initially exponentially growing modes such as shear instabilities of the longshore current. Neutrally stable modes such as edge waves will be characterized by a zero imaginary frequency component. The left panel of Figure 6 shows the resulting eigenvalues for a wavelength of ~105 m for a situation involving a plane beach and a peak longshore current speed of about 1 m/s. In this case, the linear instability analysis gives rise to several edge wave modes along with a shear instability mode. Also evident is the presence of a number of spurious modes near the origin. These modes are generated either due to rapidly varying solutions that are not adequately resolved by the discretization (such as incident gravity waves) or by a continuum of physical solutions that can not be expressed within a discretized model. The occurrence of such spurious modes in the solution of linear instability problems is commonly cited in the literature and methods to isolate them from true physical solutions exist. We isolate spurious modes by carrying out a convergence analysis and utilizing the reciprocal eigenvalue drift ratio as suggested by Boyd (2001).

In the right panel of Figure 6 the growth rate of the shear instability mode is shown as a function of longshore wavenumber. Compared are the original rigid lid solution of Putrevu and Svendsen (1992), our solution including surface elevation effects but neglecting wave-current interaction, and our solution

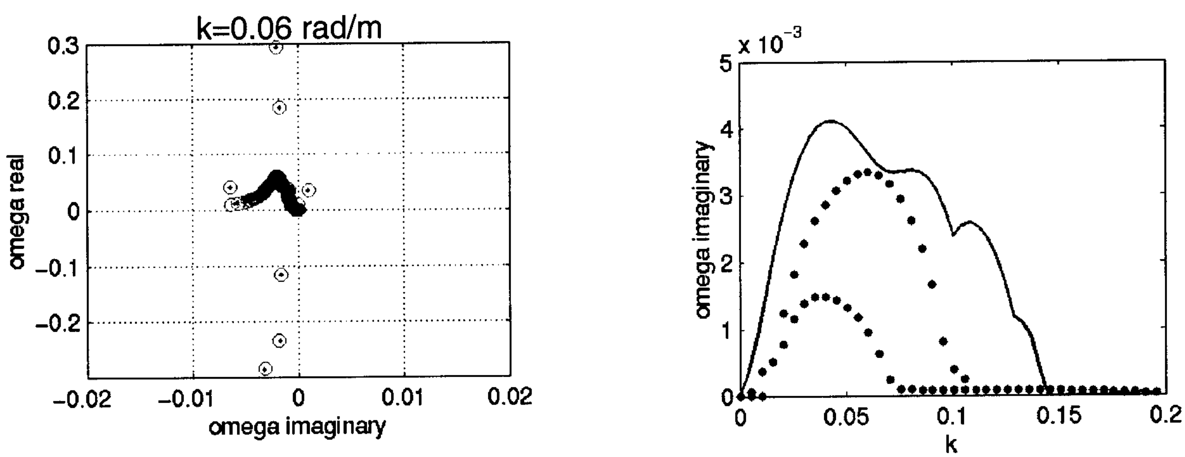

Figure 6: (left panel) Real part of the radial frequency versus the imaginary part of the radial frequency for motions at radial wavenumber k=0.06 rad/m. Positive imaginary frequencies indicate an exponentially growing mode, negative imaginary frequencies indicate exponentially decaying modes. The edge wave modes, shear instability modes, and spurious modes can be seen. (right panel) Imaginary part of the radial frequency versus wavenumber for the rigid lid solution (black line), without wave-current interaction (red) and with wave-current interaction (blue).

Our results indicate that the growth rate of the instabilities is reduced by the effect of wave-current interaction. The primary mechanism responsible for the growth rate reduction is work done by the circulation on the waves in regions where wave shoaling due to opposing current velocities occurs. We

also find that the effect of wave refraction due to the circulation is not as pronounced. A publication regarding this aspect of our work is currently in preparation (Jiao and Özkan-Haller, 2003).

IMPACT/APPLICATIONS

This study sheds light on the processes that are important in the low frequency range of the energy spectrum, such as interactions between low frequency waves and response of the low frequency environment to external forcing. This study can also serve as a benchmark for other studies that do not explicitly resolve the time-varying low frequency wave field but instead focus only on the mean circulation. Results obtained here should also be relevant to studies that are not restricted to low frequency motions, but where the low frequency motions are embedded in higher frequency oscillations, making the processes difficult to identify.

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